MINISTRY OF AGRICULTURE, FISHERIES AND FOOD

FISHERY INVESTIGATIONS
Series II, Volume XXV, Number 10

The abundance of hake off South Africa

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LONDON: HER MAJESTY'S STATIONERY OFFICE
1968

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ABSTRACT

BETWEEN Cape Town and Walvis Bay an echo survey for hake within about 4 fm of the bottom was made in HMS HECLA in February 1966. A Humber echo sounder was used which resolves signals from fish into individual traces. With a statistical treatment of the results, it has become possible to estimate the sizes of fish and thus density in numbers per cubic metre. Hence a length distribution of fish as stock can be estimated acoustically.

INTRODUCTION

THIS paper describes a method for estimating the absolute abundance of fish targets in size groups by acoustic methods. The fish cannot be identified acoustically and so acoustic survey should be supported by catches. In an exploited area, catches of the commercial fleet can be used for identification. In an unexploited area, the acoustic method endows the research vessel with the sampling power of a commercial fleet.

The method was first used on board HMS HECLA off South Africa in February 1966. Scientists from the Fisheries Laboratory, Lowestoft, Kelvin Hughes Limited, the Department of Commerce and Industry, Cape Town, the White Fish Authority, London, and the University of Cape Town executed the survey, which was made between Slangkop Point and Walvis Bay. The cruise track is shown in Figure 1. Single fish were recorded and counted and then the counts were treated in a statistical manner. Although the most powerful and sophisticated echo sounder for fish finding in the world was used, the same technique can be used with any calibrated echo sounder recording fish as single fish.

EQUIPMENT

A Kelvin Hughes Humber echo sounder was used in a 'Lollipop' body made by the National Institute of Oceanography. It was towed from the port side of HMS HECLA on a boom. This machine has a source level of 128.9 db ref 1 μbar; the transducer measures 6λ by 4λ (the first minima in echo are at 9° and 14° from the axis of transmission) and it transmits at 30 kHz. A 'Triggered Pen Recorder' scans a distance of four fathoms off the bottom and records the discrete signals from single fish. The record is locked to the bottom echo, as is also the CRT display. The transducer was calibrated in the tank at the Kelvin Hughes factory. The amplifier was controlled with a signal injector; its response was linear over the range used. Signals in μV were converted to db using: 1 μbar=34 db above 1 μV. The signal injector was also used to measure noise levels.

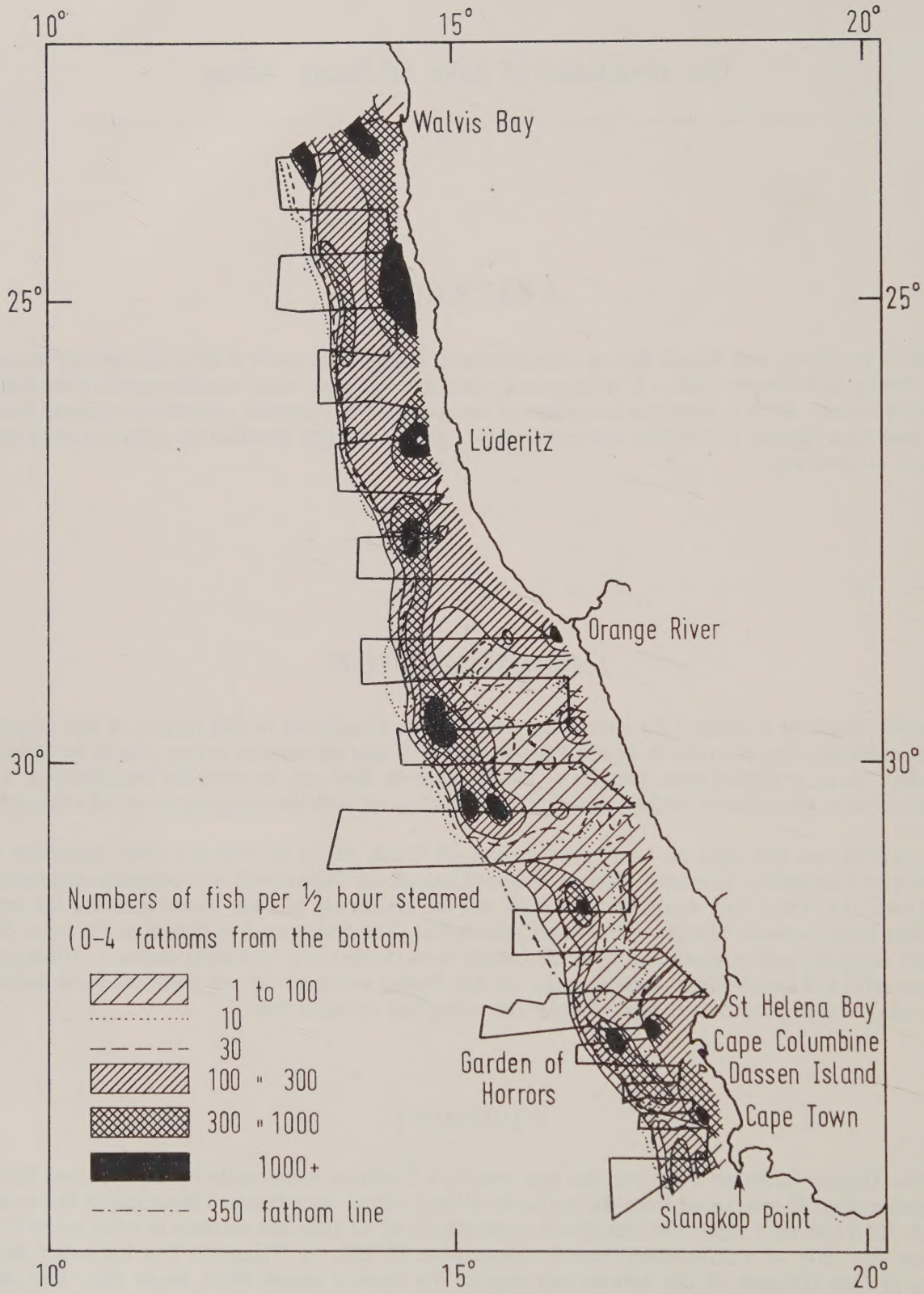
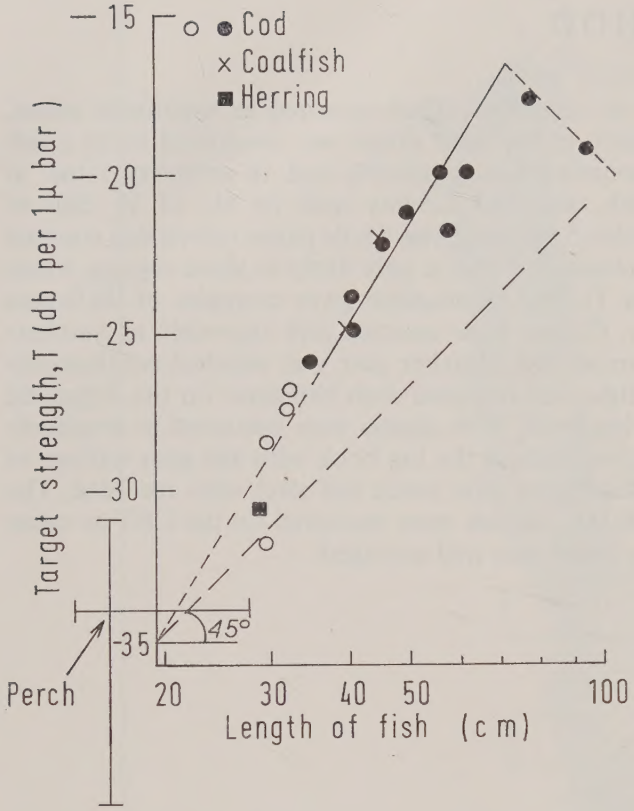


Figure 1 Results of the hake survey made by HMS HECLA off South Africa in February 1966, shown as the distribution of single fish in the 0–4 fm scan of the Triggered Pen Recorder of the Humber gear in each half-hour steamed.

METHOD

On the Triggered Pen Recorder, fish were recorded as single fish. They appeared as hyperbolic traces, or as 'blobs'. A 'blob' of more than three transmissions at the same range was considered to be a fish trace. On occasion the 'blobs' were so dense that counting was impossible and an arbitrary value, at the higher level of counts distinguishable as single fish, was used. Counts made by Mr. G. H. Ellis of Kelvin Hughes Limited and myself at sea agreed to within 5 per cent. The whole paper record was counted again by an independent team in the laboratory at Lowestoft. Error is only likely in those regions where more than 1 000 fish/half hour were counted (Figure 1). The frontispiece gives examples of the traces that were counted from the Triggered Pen Recorder. Counts were summed and expressed as numbers in 0–1 (or 0–4) fm off the bottom per half-hour steamed. The Humber gear was watched continuously in half-hour periods of a watch of four hours. The time was recorded each half-hour on the Triggered Pen Recorder, on the MS 29 and in an echo survey log book. Fish signals were measured in amplitude during each half-hour period on the CRT and were recorded in the log book with the gain settings of the amplifier. Some 300–400 observations of single fish signal (and hence fish size) were recorded. The total number of single fish recorded was well over 100 000. Signals were measured on the CRT as mean signals for short periods of time, so ensuring that the signal was well averaged.



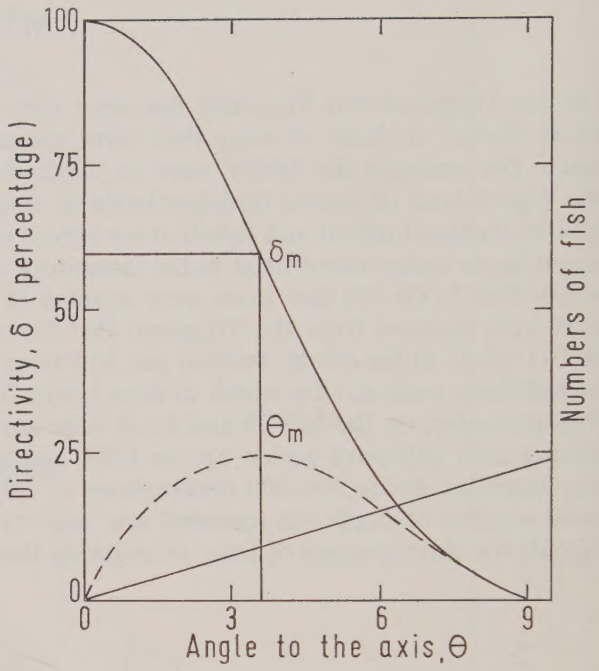


Figure 2 Dependence of target strength (T) on the logarithmic length of fish (Cushing 1964; based on the measurements of Midttun and Hoff 1962, Cushing *et al.* 1963, and Harden Jones and Pearce 1958).

Figure 3 Distribution of received signal in angle θ about the mean, θ_m. The left ordinate is scaled in directivity, δ; δ_m corresponds to the mean angle, θ_m. The right ordinate is an arbitrary scale in numbers of fish (squared). The broken line shows the product distribution of directivity and numbers of fish.

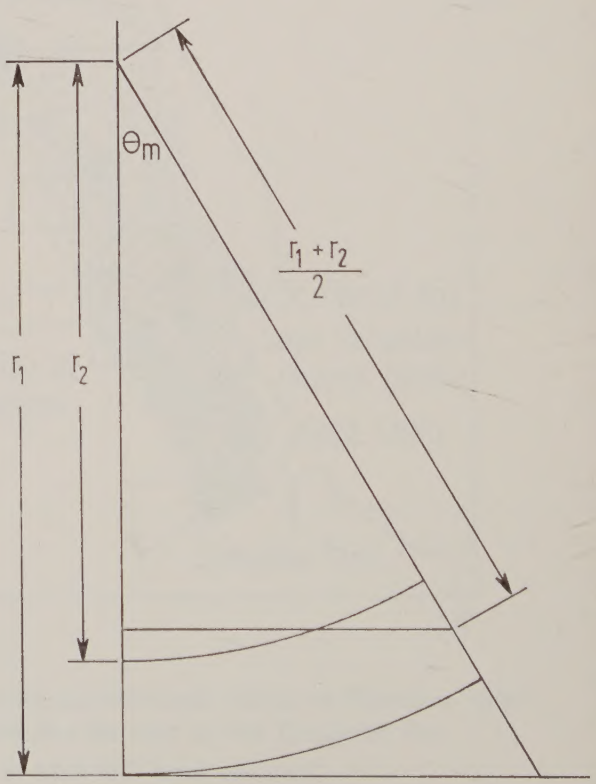


Figure 4 The mean height above the bottom of a target between ranges r_1 and r_2 and at an angle θ_m to the axis. Mean height above bottom $= r_1 - \frac{1}{2}.(r_1 + r_2) \cos \theta_m$.

THEORY

THE SIGNAL STRENGTH OF FISH TARGETS

The sonar equation (Horton 1959) is, in db ref 1 μbar, $E=S+T-2H$, where

S is the source level (128.9 db);

H is the one-way propagation loss comprising spreading and attenuation ($H=\frac{a.r}{100}+20 \log r$, a being the attenuation coefficient and r the range in yards);

T is the target strength of a single fish of a given size;

E is the observed echo level, or signal strength.

Target strength, for a given length of fish, is taken from Figure 2 (Cushing 1964, after Midttun and Hoff 1962, Cushing *et al.* 1963, and Harden Jones and Pearce 1958).

At any range, signals are received from targets at an angle θ to the axis, between 0° and the first minimum. Beyond the first minimum, signals can be received from the side lobes; in echo, however, they are unimportant, except at very short ranges. In θ, there is a distribution of directivity, δ, from 100 per cent on the axis to zero at the first minimum. There is also a distribution of fish targets, increasing in θ from the axis to the first minimum as the square of the angle, for angles less than 20°. The product of the two distributions reaches a maximum at a middle angle, θ_m, with a standard deviation in directivity (Figure 3). The broken line in Figure 3 shows the distribution of received signal from fish about the mean angle θ_m. On average all signals from fish are considered to be received from θ_m.

THE SHIFT IN DIRECTIVITY TOWARDS THE AXIS AT MEDIUM TO MAXIMUM RANGES

At maximum range, the signal from a fish of given size is received from the axis only. So there is an intermediate point in range beyond which θ_m tends towards zero and δ_m tends towards 1. When finally $\delta_m=1$ and $\theta_m=0$, the signal is received from the axis only, at maximum range. In the Humber gear, 1 μbar = 34 db above 1 μV. So target strength, T, can also be expressed in μV. Let $T.r_{max}^{-2}=T.r_z^{-2}.\delta_{min}$, where

r_{max} is the maximum range on the axis at which a fish of target strength, T, can be detected;

r_z is the range at which $T.r_{max}^{-2}$ is recorded at θ_{min}, the first minimum.

Because δ is zero at the first minimum, δ_{min} is defined as the directivity coefficient at which the signal reaches the minimum recordable signal (MRS), at a conventional signal to noise ratio. So $\delta_{min} > 0$. At any range between r_z and r_{max}, r_x, values of θ_{min} can be estimated from $\delta_{min}=r_z^2/r_{max}^2$ and the dependence of δ on θ shown in Figure 3. Then θ_m' can be estimated from the new value of θ_{min}', using distributions of directivity for scales of θ, where θ_m' is the mean angle at range r_x with directivity coefficient δ_m'.

So, given T, values of r_{max}, r_z and r_x are calculable. Theoretical values of signal strength ($T.r^{-2}\delta_m$) are calculable from r_0 (1 m from the transducer) to r_z and from r_z to r_{max}, using the new values of θ_m' (and hence δ_m') for each value of r_x. Figure 5 shows theoretical values of signal strength for a range of fish sizes from 20 cm to 90 cm, using a Humber gear in a towed body.

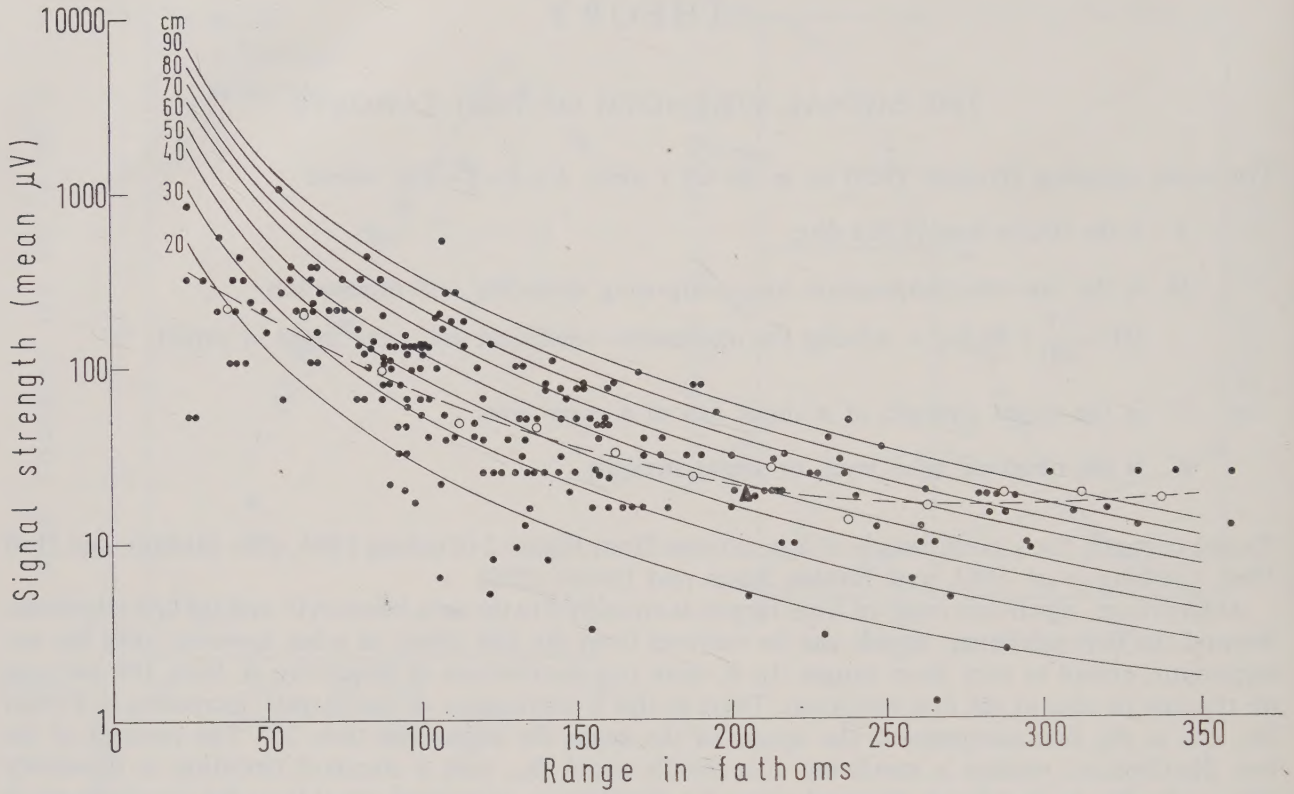


Figure 5 Theoretical curves of signal strength (for fishes of 20 cm to 90 cm in length) on range. The points represent observations of average target strength, each measured for a short period of time on the CRT, during the cruise of HMS HECLA, off South West Africa, in February 1966. The broken line shows the trend of mean target strength with range in depth. The black triangle at 210 fm, between the line for a 40-cm fish and that for a 50-cm fish, indicates the mean length (46 cm) of fish caught at that depth.

THE VOLUME SAMPLED FOR A FISH OF A GIVEN SIZE

A square transducer examines *range shell volumes* of $2\pi(r_1^3—r_2^3)$ (1—cos θ) /3 cubic metres, between r_1 and r_2 in range and from the axis to angle θ, where the thickness of the shell in metres is $(r_1—r_2)$ and θ is measured to the first minimum (Richardson *et al.* 1959). For a rectangular transducer, the range shell volume is given by $2\pi(r_1^3—r_2^3)$ (1—cos $\sqrt{\theta_\alpha.\theta_\beta}$)/3 cubic metres, where θ_α and θ_β are the angles subtended by the major and minor axes of an ellipse formed as conic sections of the beam of the rectangular transducer. The range shell volumes are calculated for an elliptical range shell bounded in angle by $\theta_{\alpha\min}$ and $\theta_{\beta\min}$. This step was made by my colleague Mr. J. G. K. Harris.

For a fish of given size, the range shell volumes are calculated in depth to r_z. From r_z to $r_{\max}$, $\theta_{\alpha m}$ and $\theta_{\beta m}$ are calculated as given above. Such volumes are the average volumes in which a fish of the size specified can be detected. Range shell volumes for steps in θ are *range shell sectors*. Each range shell sector in angle θ is multiplied by the appropriate directivity coefficient. From r_z to $r_{\max}$, δ for a given angle θ will increase with increasing range, as shown above. The sum of the weighted sectors is the *effective volume sampled*. This procedure takes into account the chances of detection within the volume sampled.

THE CONVERSION OF NUMBERS PER UNIT DISTANCE TO NUMBERS PER UNIT VOLUME

The ship steams with the minor axis of the transducer beam ellipse fore and aft. The minor axis is 2D $\sin\theta_{\beta\min}$. If the ship steams at 9 knots, the number of exclusive volumes sampled in that time is given by 9 000/2D $\sin\theta_{\beta\min}$. If n fish were recorded in half an hour's steaming, then the number of fish per *effective volume sampled* is n.2D $\sin\theta\beta_{\min}$/9 000. Hence the numbers of fish recorded as single fish on the Triggered Pen Recorder are estimated as per unit volume.

Fish signals are recognized in successive transmissions and are counted in the total volume sampled by the echo sounder during a time period. The total volume is of complex shape and the distribution of signals within that volume is also complex. This is why we consider the number of exclusive volumes in the distance sampled. The total volume estimated in this way is given by

$$\tfrac{2}{3}.\pi(r_1^3 - r_2^3)\ (1 - \cos\ \sqrt{\theta_\alpha.\theta_\beta}) \cdot \frac{D}{2r_1\ \sin\theta_{\beta\min}}.$$

Because of the overlap between the volumes in successive transmissions, the true volume sampled is somewhat larger. If it is assumed that the rate of transmission is fast enough to allow all parts of a rectangular block surrounding the ellipsoidal shell to be sampled, the problem is simple. The upward bias in estimated volume is the ratio of the volume of the rectangular block, tangential to the surfaces of the ellipsoidal shell, to that of the ellipsoidal shell itself; i.e.

$$\frac{2r_1\sin\theta_\alpha.2r_1\sin\theta_\beta\left[(r_1 - r_2) + r_1\left(\frac{1}{\cos\sqrt{\theta_\alpha.\theta_\beta}} - 1\right)\right]\cos\sqrt{\theta_\alpha.\theta_\beta}.2r_1\sin\theta_{\beta\min}}{\tfrac{2}{3}\pi(r_1^3 - r_2^3)\ (1 - \cos\sqrt{\theta_\alpha.\theta_\beta}).D} = 1.21.$$

So the upward bias in the estimate of volume is 21 per cent and all densities should be multiplied by 0.826 (1/1.21). I am grateful to Dr. Glenn Johnson of Dalhousie University for pointing out the error due to the overlap of sampling volumes.

THE AVERAGE HEIGHT ABOVE THE BOTTOM OF FISH TARGETS

The mean height of fish above the bottom is at θ_m and is given by $r_1 - \frac{1}{2}.(r_1 + r_2)\cos\theta_m$, where $(r_1 - r_2)$ is the thickness of the shell scanned. The derivation is shown in Figure 4. It can be calculated for $\sqrt{\theta_{\alpha m}.\theta_{\beta m}}$ for the rectangular transducer. The values of $\cos\theta_m$ must be corrected between r_z and r_{max} as described above.

SUMMARY

The height of fish above the bottom can be specified, with a standard deviation. The numbers of fish of given sizes can be estimated as per unit volume. These estimates are based on the statistical manipulation of the acoustic parameters of the system. Each estimate is based on the numbers of single fish per unit time in the scans of 0–1, 1–2, 2–3 and 3–4 fm on the paper record.

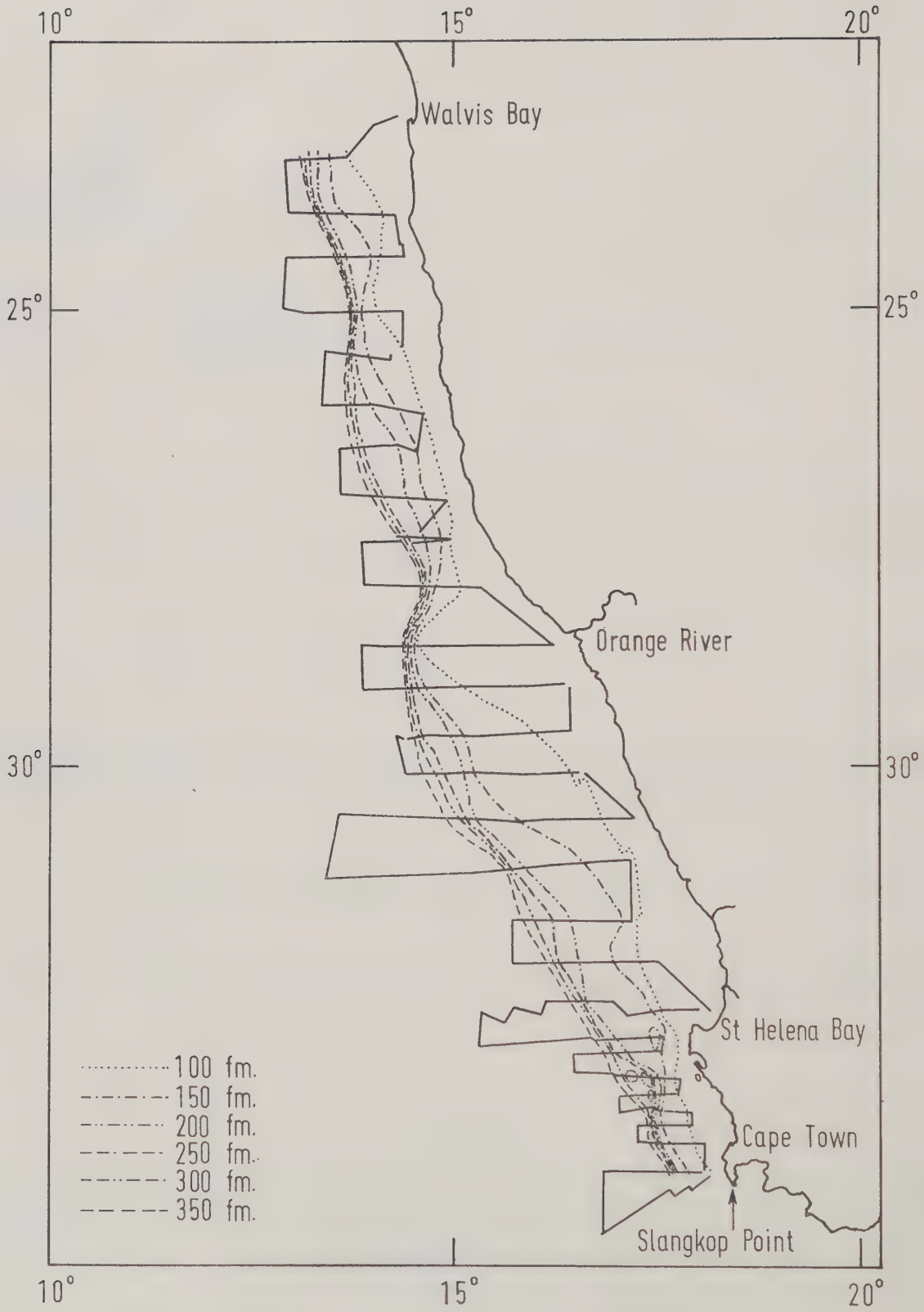


Figure 6 A bathymetric chart of the survey area, based on the corrected depths recorded by the officers of HMS HECLA.

RESULTS

GENERAL

The first result is that shown in Figure 1, giving the distribution of single fish within about 4 fm of the bottom in each half-hour steamed along the cruise track. The most important point about this chart is that the traditional fishing grounds for hake off Cape Town and Cape Columbine are shown clearly, particularly those off Dassen Island and in the Garden of Horrors. Then the newly discovered grounds off Lüderitz and south of the Orange River are also shown. Hence there is some reason to believe that the single fish recorded were really hake. The regions of abundance recorded by the echo sounder correspond with those on the fishing grounds. Figure 6 shows the depth contours for the areas, depths being contoured at 100, 150, 200, 250, 300 and 350 fm. It will be seen that there are three bathymetric regions, i.e. the very varied area between Slangkop Point and St. Helena Bay, the extensive but sloping shelf between the Bay and the Orange River (with a wide area of less than 100 fm), and the narrower shelf with a gradual slope between the Orange River and Walvis Bay. Fishing results in baskets/hour, averaged by statistical square during the period of survey, are shown in Figure 7 (1 basket of fish weighs 100 lb).

SIZES OF FISH FROM ESTIMATES OF SIGNAL STRENGTH

Figure 5 shows the curves for target strength of fishes of 20–90 cm in length from depths of 50–700 yd (25–350 fm). The theoretical curves are corrected for directivity as described. The points on the figure are the signals observed on the CRT.

Observations of signal strength in μV were taken in each half-hour at noted gain settings. Each observation was effectively the average of a number of values. The CRT was examined for perhaps a minute until a good mean value was taken. The points on Figure 5 are averaged signals and should be regarded as being received from angle θ_m. In general, the signals appear to be in the fish size range of 20–90 cm. At most depths there are some fish smaller than 20 cm. The broken line across the curves indicates the mean signal at intervals of 25 yd in range. Variance about the mean line has the following components: sampling, fish size and beam directivity. The smaller fish live in shallow water and the larger fish in deeper water, as might be expected. Three length distributions of fish, all taken from about the same depth, are available from the Cape Town grounds, the Cape Columbine grounds and off Lüderitz (Figure 8). The mean length is 46 cm in a mean depth of 205 fm. This point is marked on Figure 5 as a black triangle and it is very close to the mean curve of signal on range.

The noise level from the whole system including the towed body was, on average, about 1–2 μV; in bad weather it probably rose to 3–5 μV. One would expect the noise level to increase in shallower water and, indeed, the trend of lowest signal with depth might well indicate the trend in noise level with depth. Thus, in a general way, the Humber gear and the trawls were examining the same sizes of fish. The mean selection point for the trawls used was probably about 35 cm. The chance of acoustic detection against noise level for a 20-cm fish decreases with depth, so for the shelf there is a mean acoustic selection point of about 25 cm. When the numbers of fish are given by length groups, the lowest length group is seen to be 36–42 cm (Figure 12). So it is likely that this length group can be compared properly with that sampled by the trawl. The trawl catches were 90–95 per cent hake and so it is likely that most of the single fish were hake. It remains possible that signals estimated outside the areas of catching could be attributed to fish other than hake of the estimated sizes.

In Figure 9 the length of fish/depth distributions are split by regions, lengths being estimated from Figure 5. Region 1 is Cape Town to Cape Columbine; Region 2 is Cape Columbine to 29°30′S; Region 3 is 29°30′S to just north of Lüderitz; Region 4 is north of Lüderitz to 25°30′S, and Region 5 is 25°30′S to Walvis Bay. In the first region, Cape Town to Cape Columbine, the fish lie in depths of between 100 and 350 fm. They range from 20–50 cm in 100 fm to 50–80 cm in 300 fm. The increase in size with depth

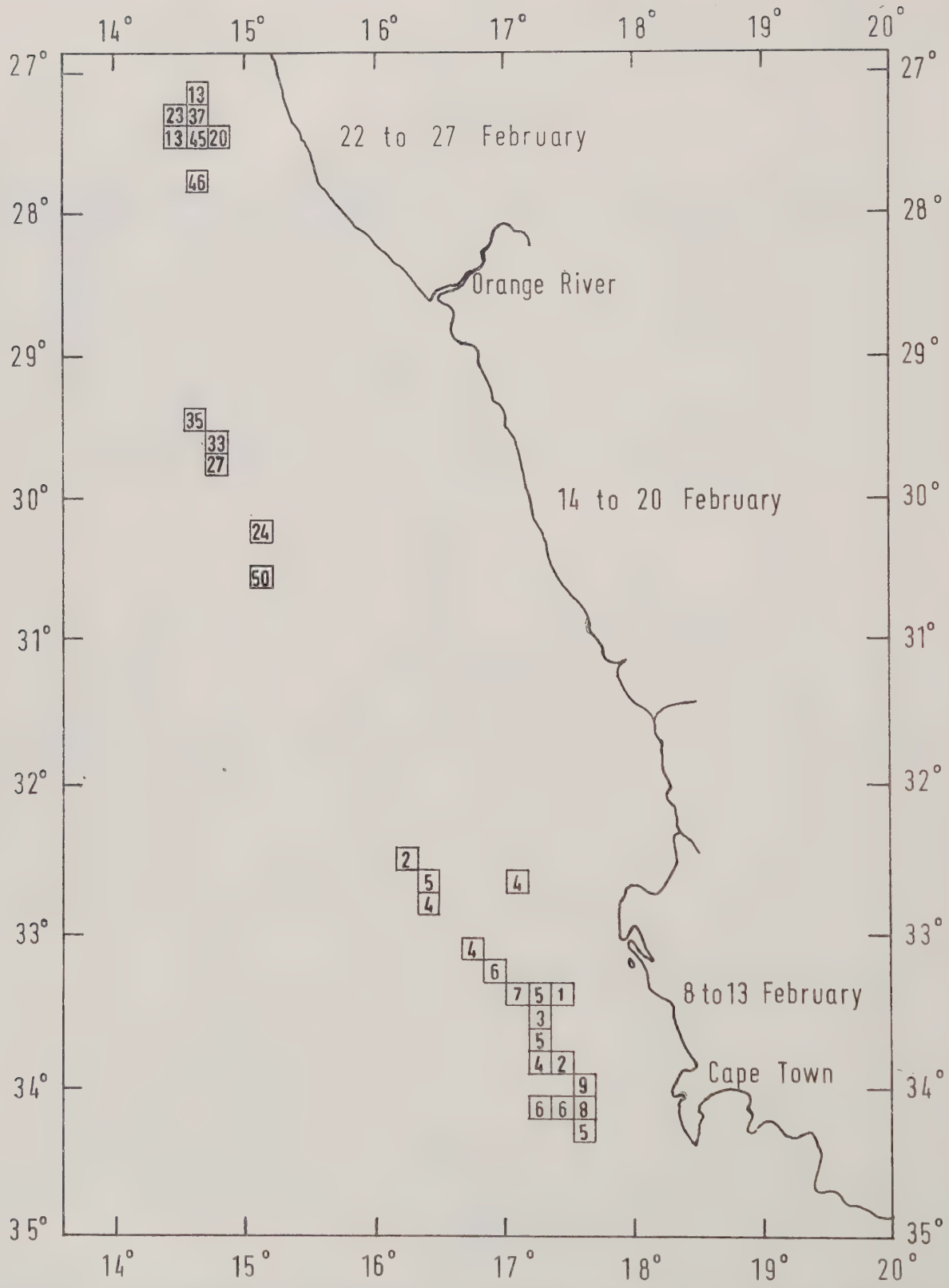


Figure 7 The catches/effort (in baskets/hour) for the period during which the cruise of HMS HECLA was carried out. The data on catch/effort were collected by Mr. B. C. Bedford in the port of Cape Town, where a basket of fish weighs 100 lb.

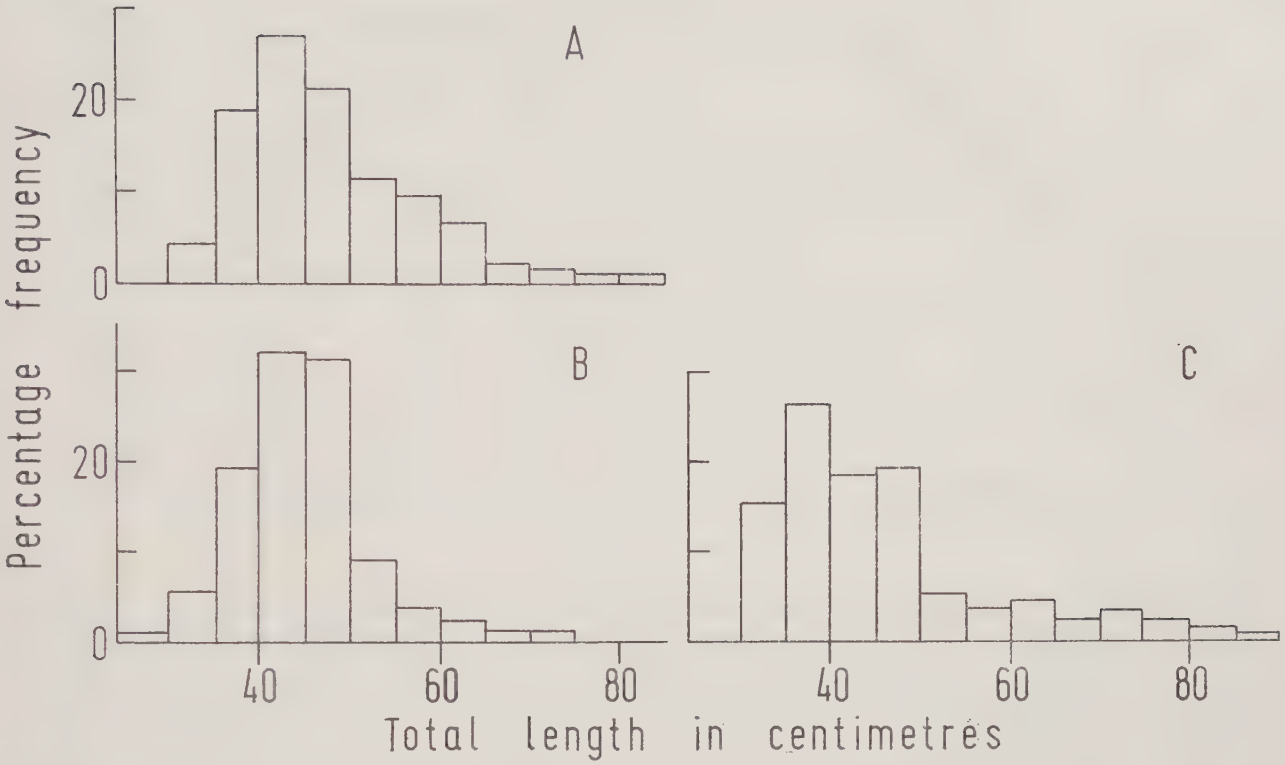


Figure 8 Length distributions of hake caught from: A, the Cape Town grounds; B, the Cape Columbine grounds; C, the grounds off Lüderitz, all in roughly the same depth (ca 220 fm).

is roughly 10 cm for 50 fm. In the next region northwards the slope is practically the same. In 50 fm there are fish from 20–25 cm; in 150 fm the fish range from 30–60 cm. Northwards, again, to the Orange River there is still a trend of size with depth, but the slope of the regression is slightly less, about 6 cm in length for each 50 fm in depth. There is a much greater spread of sizes: in 100 fm the fish range from 20-80 cm, about a mean of 43 cm; in 250 fm they range from 20–90 cm, about a mean of 62 cm. In both of the regions north of the Orange River there is no detectable trend of size with depth.

THE MEAN HEIGHT OF SIGNALS ABOVE THE SEA BED

The numbers of single fish were counted in each of four levels on the paper record from the Triggered Pen Recorder: 0–1 fm, 1–2 fm, 2–3 fm and 3–4 fm off the bottom. The echo sounder records fish not in a band 0–1 fm off the bottom, but in a shell tangential to the bottom. We consider the fish to be distributed about an angle θ_m, and at this angle the fish recorded as at 0–1 fm off the bottom can be more than 1 fm off the bottom. As shown in Figure 4, the mean height above the bottom in the whole shell scanned is $r_1 - \frac{1}{2}.(r_1 + r_2) \cos 0_m$. The mean signal is assumed to be received from $\sqrt{\alpha\theta_m.\beta\theta_m}$, taking into account the rectangular beam patterns of the transducer. The value $\sqrt{\alpha\theta_m.\beta\theta_m}$ was corrected for changes in directivity between r_z and r_{max} for a 46-cm fish. The mean height above the bottom for a 46-cm fish estimated in this way is given in Table 1. Because θ_m is close to the axis in depths greater than 150 fm, the overestimate of true depth for a 20-cm fish is much less. When the ship is rolling, the angle θ_m swings with respect to the vertical by an equal amount and so we may regard the average signal

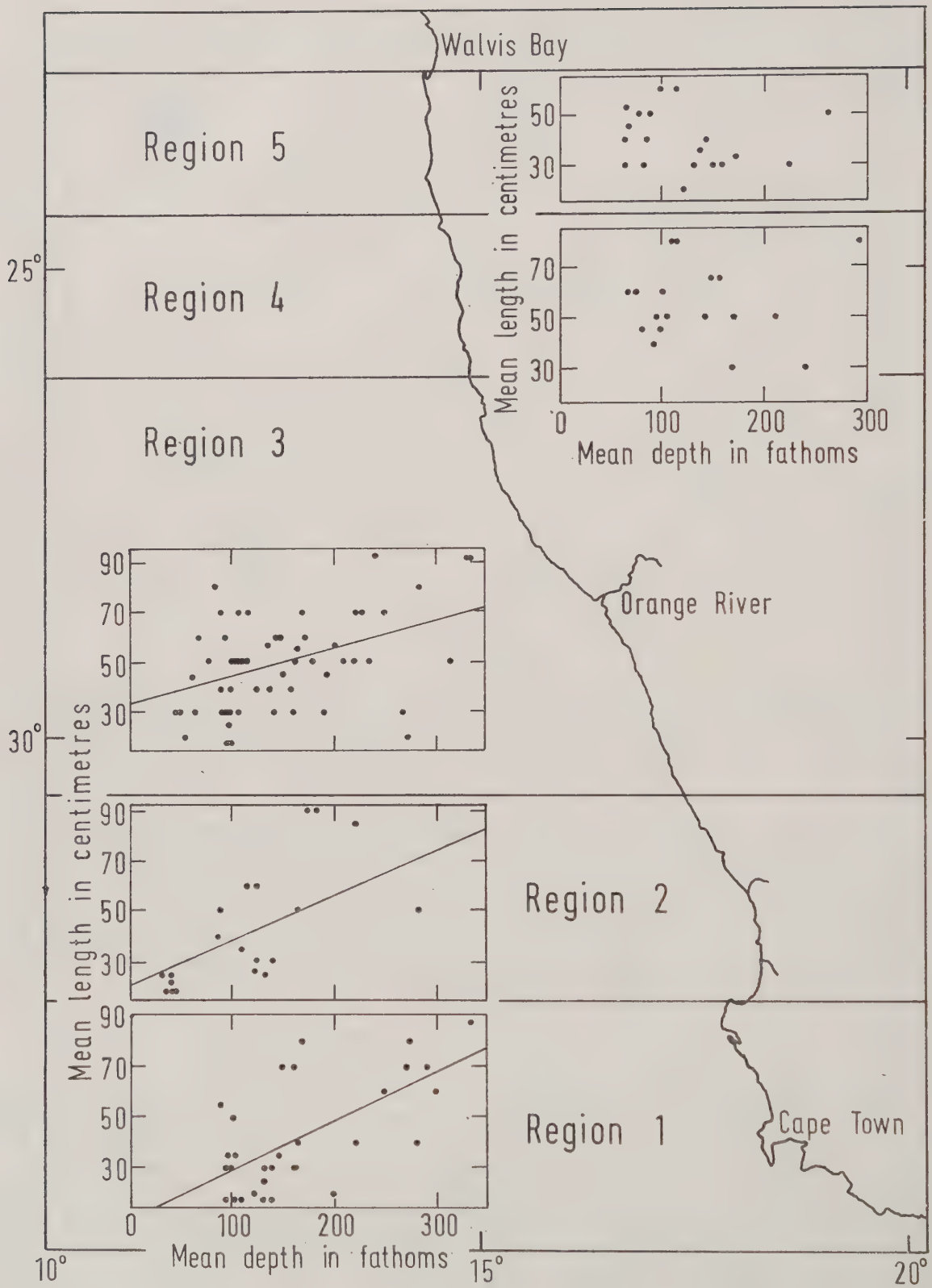


Figure 9 Lengths of fish, as estimated from Figure 5, at different depths in each of five regions between Cape Town and Walvis Bay.

Table 1 The mean height above the bottom of a 46-cm fish in the 0–1 fm scan, i.e. indicated at 0.5 fm above the bottom.

Depth (fm)	True mean height above bottom (fm)
50	0.66
100	0.82
150	0.98
200	1.11
250	1.17
300	1.27
350	1.27

as being received from θ_m, as if the ship were not rolling. The variance on the estimate, however, increases with roll. Because more fish are found at a greater angle to the vertical, the variance distribution is biased towards greater angles. Such an estimate is reasonable so long as targets are randomly distributed within the depth scan examined on the Triggered Pen Recorder. Where fish are not detected because they are 'hard down', or because of boulders, the problem is insoluble unless the pulse length is very much reduced. Hence, by appropriate signal processing it should be possible to obtain a true vertical distribution by using the Humber gear without any form of stabilization. A stabilized transducer would reduce the variance, but also the rate of sampling. An analysis of the vertical distribution of the fish records in the four depth scans is shown in Table 2.

Table 2 Vertical distribution of the fish records in the four depth scans.

	Fm off bottom	Numbers of fish		Day numbers ÷ 2.105*	Day/night ratio
		Day	Night		
(a)					
In the northern half	0–1	12 184	1 654	5 788	3.5
of the survey area	1–2	11 755	2 162	5 584	2.6
(i.e. north of the	2–3	8 284	2 616	3 935	1.5
Orange River)	3–4	16 601	4 020	7 886	2.0
(b)					
In the southern half	0–1	6 097	1 846	2 897	1.6
of the survey area	1–2	5 604	3 610	2 662	0.8
(i.e. south of the	2–3	6 605	3 109	3 133	1.0
Orange River)	3–4	24 558	11 693	11 667	1.0

**Note* The factor 2.105 is the ratio of daylight track to night track within the 360 fm line

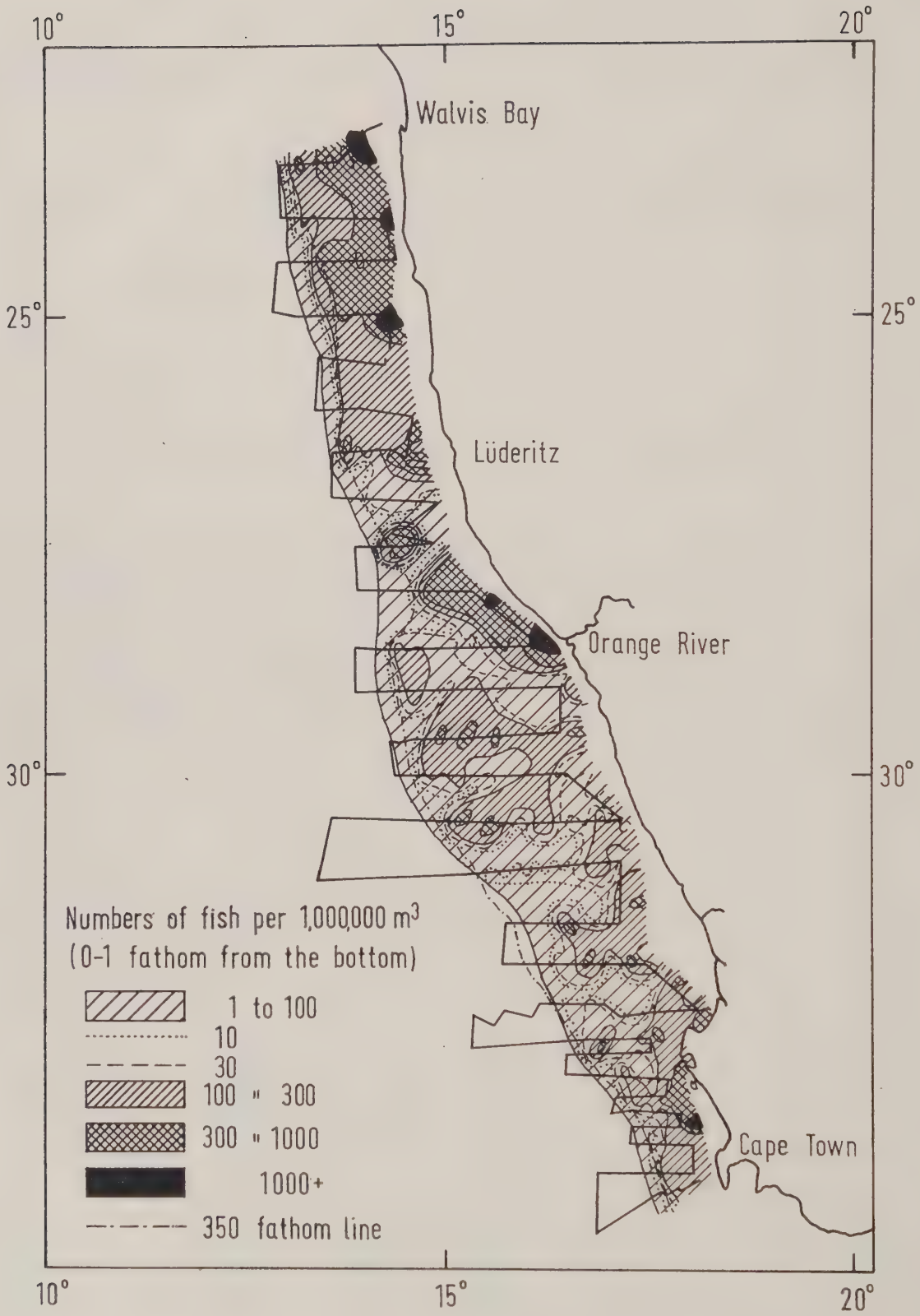


Figure 10 Fish densities, as numbers per 10^6 cubic metres, in the 0–1 fm scan off the sea bed.

In the southern half of the survey area, there is no difference between day and night numbers of fish at any of the depths examined. In the northern half of the area, there were 1.5–3.5 times as many fish found in a given scan level in the daytime as at night. There is a trend in the day/night ratio as the scan was made further from the bottom, suggesting that the nightly vertical migration was of rather limited extent—of not much more than 5 fm. An interesting point about the observations in the southern half of the area is that 3 or 5 times as many fish were recorded in the scan 3–4 fm off the bottom as in the other scans. This suggests that any vertical migration was masked by another factor. The most important conclusion is that the changes in abundance due to vertical migration are less than the differences between depth contour levels, and so the contoured charts represent estimates of abundance unbiased by vertical migration. It is true that in the northern half of the area the day/night factor reaches 3.5. So the best estimate of abundance would be in the scan 0–4 fm off the bottom.

NUMBERS PER UNIT VOLUME

The density of fish per unit volume (numbers per 10^6 cubic metres) is shown in Figure 10, which gives the distribution as estimated from the scan of 0–1 fm from the bottom. Figure 11 shows the distribution of fish as estimated from the scan of 0–4 fm from the bottom. The distribution differs from that in Figure 1. The latter is biased towards the deeper water, the echo sounder sampling a larger volume, and the expression 'numbers per half-hour steamed' does not take this point into account.

A Granton trawl is 60 ft wide and 6 ft high at the mouth, presenting an opening of about 40 square metres. The density of fish is given in numbers per 10^6 cubic metres. This unit volume represents a surface of 10^4 square metres at each transmission. The trawl sweeps a surface 2 metres thick, and an even acoustic density over the distance at one hour's haul represents a volume of 2×10^4 cubic metres. With the trawler steaming at 3 knots, the trawl 'filters' 2.4×10^5 cubic metres per hour. So an acoustic fish density of 1 per 10^6 cubic metres represents a volume sampled by the trawl of 2×10^4 cubic metres and, for an hour's haul, a catch of 12 fish. Table 3 converts numbers per unit volume to fish catches in numbers and weights (a fish of 46 cm, the mean length in the catches, weighs 0.80 kg).

Table 3 Conversion of numbers of fish per unit volume to catches by numbers and by weight.

Contour level (numbers per 10^6 cubic metres)	Catch/hour in numbers	Catch/hour in weight (kg)
1	12	9.6
10	120	96.0
30	360	288.0
100	1 200	960.0
300	3 600	2 880.0
1 000	12 000	9 600.0

During the period of the survey catches were made on the Cape grounds (10 baskets/hour or 0.5 tons/hour), the Orange River grounds (30–50 baskets/hour or 1.5–2.5 tons/hour) and the Lüderitz grounds (30–50 baskets/hour or 1.5–2.5 tons/hour). The distribution of catches is shown in Figure 8. In Figure 10 the Cape grounds are contoured at 100 per 10^6 cubic metres or 1 ton per hour; the Lüderitz and Orange River grounds are contoured at 300 to 1 000 per 10^6 cubic metres or 3.0 to 10.0 tons per hour. The overlap

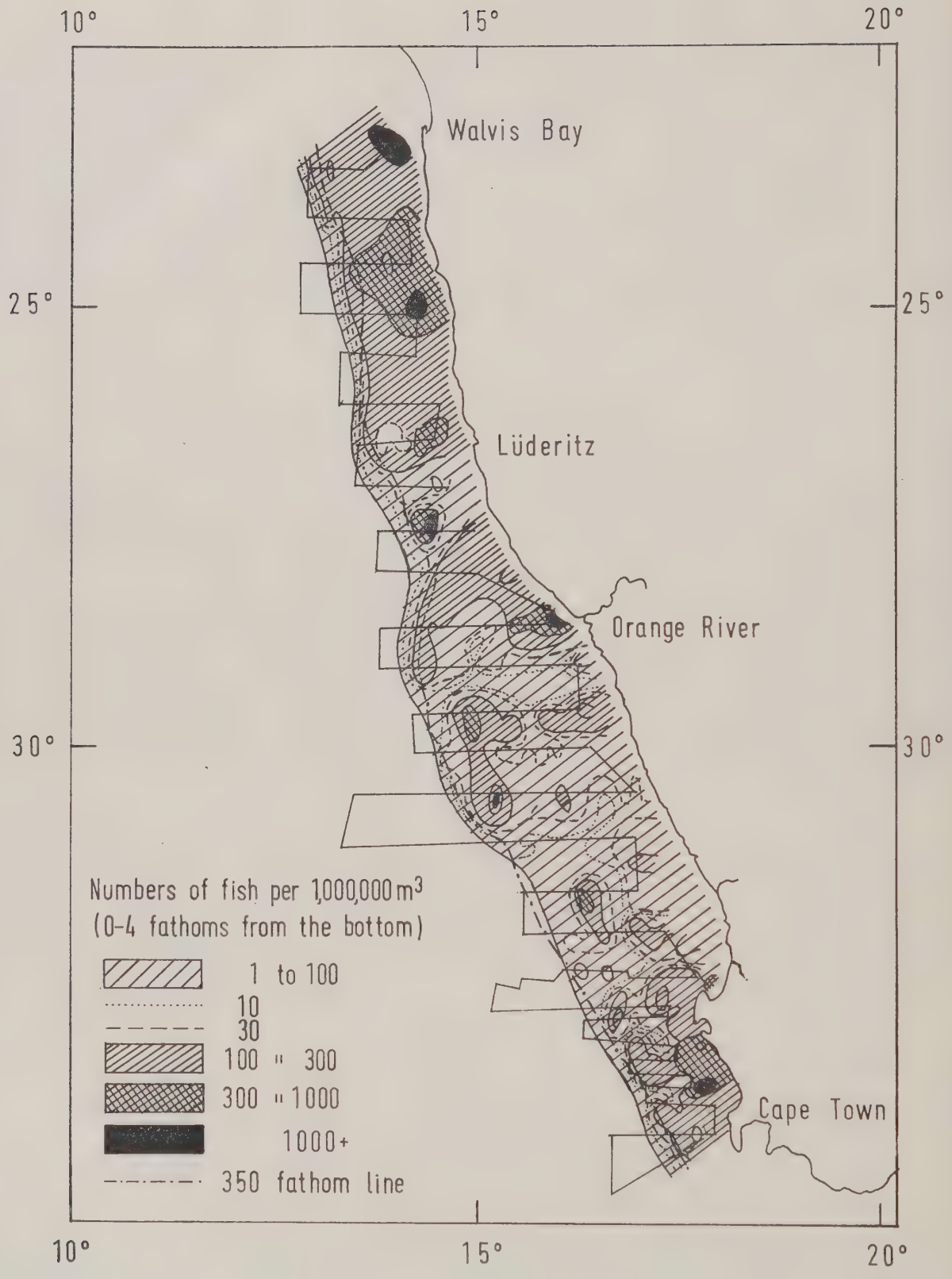


Figure 11 Fish densities, as numbers per 10^6 cubic metres, in the 0–4 fm scan off the sea bed.

error referred to above remains in the estimates of density given in Figure 10, as the value of the figure lies in the comparison of relative densities between areas. So the acoustic density is 21 per cent higher than the true density. The agreement between the acoustic method of estimation and the actual catches is not bad.

THE ESTIMATE OF ABUNDANCE

An estimate of abundance can be based on the scan 0–1 fm from the bottom or on that 0–4 fm from the bottom. The first is an estimate of the catchable population, about one fm off the bottom in true depth. The second is an estimate of the population migrating vertically. Because the fish sampled by the upper scans were not catchable, the possibility remains that fish other than hake (but of the same size) were being recorded. The bathymetric chart (Figure 6) was combined with Figures 10 and 11 to estimate the numbers at the depth intervals 50–100 fm, 100–150 fm, 150–200 fm, 250–300 fm and 300–350 fm. These numbers were corrected for the overlap error referred to above. From Figure 5, using the line of mean signal on range, it is possible to estimate the range of mean sizes of fish at these depth intervals. Let there be N square kilometres at a fish density of n^* per 10^6 cubic metres between 100 and 150 fm. Then n^* per 10^6 cubic metres represents a surface area of n^* per 10^4 square metres and the numbers of fish are given by $N \times 100/n^*$. So the stock can be expressed in numbers per length group in the 0–1 fm scan (Figure 12a) and in the 0–4 fm scan (Figure 12b). The total for the first is 2.84×10^9 (or 2.48 million tons), the estimated stock in the 0–1 fm scan, which were probably hake, as sampled by the trawls.

By choosing the first depth interval at 100–150 fm, the first length group is 36–42 cm. It is likely that fish of this length are fully retained by the trawl and that they are adequately sampled by the echo sounder. Wherever trawls were used commercially 95 per cent of the catch was hake. Trawlers were searching most of the area north from Cape Town to Lüderitz, if rather thinly, during the cruise of HMS HECLA. Bearing in mind that fish outside the trawled areas may not be hake, the estimate remains a true estimate of numbers of fish of the sizes quoted. The error in length estimation is that about the mean curve of signal strength on range in Figure 4. Between 100 and 150 fm, sizes are recorded as >20 cm and <90 cm, but the mean size is 36–42 cm. The standard deviation in length is 38.1 cm and the standard error of the mean is 12.3 cm. Hence fish in the length group 36–42 cm could be classified in either the length group above or that below. When observations of signal strength are made on the trace of each fish counted, then such an error will be considerably reduced.

The length interval increases with length, which follows from the shape of the curve of mean signal with depth in Figure 4. Hence the number of age groups in the bigger length groups will be even greater than it is in an ordinary length distribution.

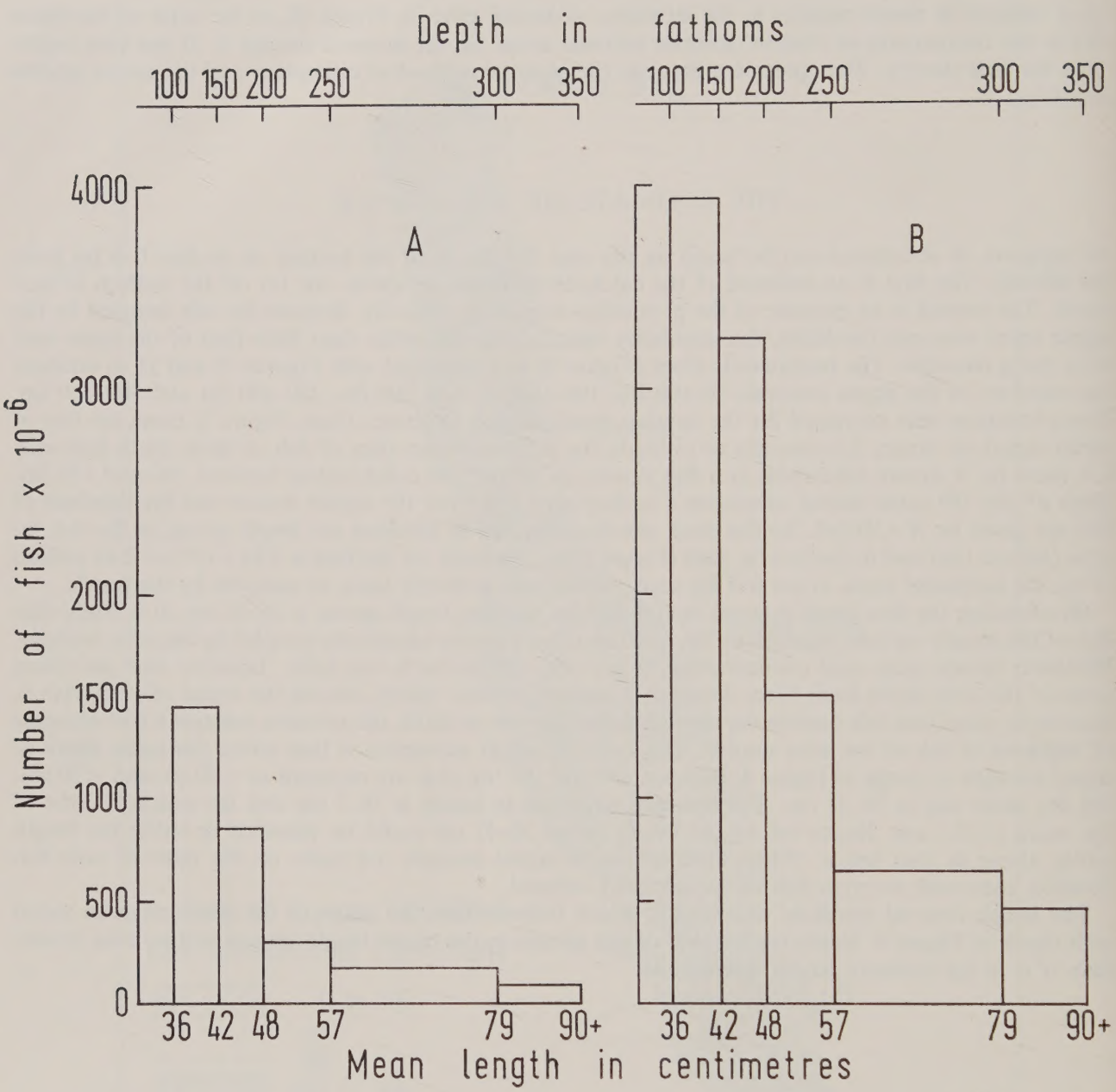


Figure 12 Length distributions in the stock of fish counted on the echo survey (a) in the 0–1 fm scan, a weight of 2.48 million tons (b) in the 0–4 fm scan.

DISCUSSION

THE ordinary commercial echo sounder puts about 1 kW of electrical energy into a rather wide-beamed transducer ($3\lambda \times 2\lambda$). The Kelvin Hughes Humber gear puts 8 kW into a narrower beam ($6\lambda \times 4\lambda$), which makes it many times more powerful. The received signals are recorded on the special high-speed Triggered Pen Recorder, which presents a four-fathom depth scale on a paper tape, six inches wide. Not only can single fish be recorded down to 350 fm and deeper, but they can be resolved by the high-speed recorder. Only with this machine could the fish be counted effectively as single fish.

The successful application of the sonar equation to signals of single fish depends upon the right statistical treatment. Signals are treated as being received from an average angle from the axis; this angle tends towards the axis at maximum range. The curves calculated in Figure 4 represent the average signal for any size of fish and range. The spread of observations represents the spread about the signal from the mean size of fish. So a proper data-collecting system would not only obtain vastly more observations of signal strength, but would stratify them by size of fish. The error in the system would be considerably reduced. Midttun (1966) has devised a method for automatically recording the signal strengths from single fish. With a similar form of signal processing it should be possible to obtain a continuous record of the fishes' true height above the bottom. The best echo survey is made with a research vessel capable of catching fish; then, numbers and sizes as recorded acoustically can be partitioned by the relative size distributions of the different species caught. Repeated surveys like that made by HMS HECLA would yield repeated estimates of stock numbers. For a population of a single species, like the hake, a comparatively small number of trawl hauls would be needed for identification. Because the distribution can be expressed in length and because estimates of mortality and growth are made yearly, there is the space of a year in which to repeat the surveys and improve the estimates. So long as the migratory circuit of the species is known, the estimates of numbers can be repeated frequently enough to yield an error. Indeed, there is no reason why good estimates of total mortality should not be made available from the length distributions. Estimates of fishing mortality can be made from the ratio of catch to stock.

The survey of HMS HECLA was originally envisaged as an exercise to delineate the relative abundances of demersal fish off the coasts of South Africa and South West Africa. But a new form of population analysis has been created. The work of Richardson *et al.* (1959), Saetersdal and Hylen (1959), and Hylen, Midttun and Saetersdal (1961) has shown that echo survey can extend the catching surveys of research vessels to something like the sampling power of a commercial fleet. The cruise of HMS HECLA suggests that the true power of the new technique lies in the capacity to estimate absolute abundance, acoustically.

ACKNOWLEDGEMENTS

I AM grateful to the Hydrographer of the Royal Navy, Rear Admiral G. S. Ritchie, D.S.C., R.N., who allowed me to work aboard HMS HECLA off South Africa and South West Africa. I am also grateful to Captain G. P. D. Hall, D.S.C., R.N., and the officers and men of HMS HECLA, who allowed me to make the greatest use of their excellent oceanographic facilities.

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Printed in England for Her Majesty's Stationery Office by W. A. SMITH (Leeds) LTD.

Dd.135718 K.7 2/68